Storm Surge Mapping for Montego Bay, Jamaica

Organization of American States
General Secretariat
Unit for Sustainable Development and Environment

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Executive Summary

Introduction

The General Secretariat of the Organization of American States (OAS), in collaboration with the USAID, has sponsored the Caribbean Disaster Mitigation Project (CDMP). As part of this CDMP, a storm hazard pilot project was developed for Montego Bay. The intention of this project was to fine-tune the surge computation and analysis procedures, so that these could be used with confidence in other countries of the Caribbean. In addition, present regulatory and risk assessment practices were evaluated in the light of the predicted storm surge findings.

At the start of the project, a computer model was used to give storm surge predictions for Montego Bay. Specifically, the output from the model included:

- Maps showing the Maximum Envelope of Water (MEOW) generated surge.
- Storm surge predictions for 10,25, 50 and 100 year return periods.

The methodology for the computation of storm surge, and the manipulation and interpretation of this data, has subsequently been subjected to a detailed review process. This has resulted in the development of a well-documented approach to storm surge computation, which has been aided by the input of Professors Robert Sorensen and Mark Johnson (of Lehigh University and University of Central Florida respectively) and which has been accepted by the engineering regulatory body in Jamaica. It is believed that the methodology proposed may now be applied with confidence throughout the Caribbean region.

This report forms the final document within the Montego Bay Storm Hazard Project. Three main components have been included. The first is the recommendation for a policy framework, for the use of storm hazard information in Jamaica. In developing this policy framework, an assessment has been made of the current practice regarding the use of hazard information by planners, engineers, and the insurance industry.

The second part of the report includes a set of guidelines for the computation, interpretation, use and presentation of storm hazard information. As part of these guidelines, some basic definitions for storm surge have been made.

The third section of the report gives a description of a case study that was undertaken for Doctor’s Cave in Montego Bay. Within this section, the storm surge models used, have been described.

Finally, the report includes a description of the entire project development, including papers presented at the October 1997 Technical Workshop. These have been presented as Appendix 1.

Current Practices and Regulatory Approach

In investigating the existing policy framework for storm hazard computation and analysis, a review was made of current practices and the regulatory approach to risk. Under this category, design practices advocated by the Jamaica Institution of Engineers were examined. These revealed well defined design criteria for: wind loading on buildings (using a 1 in 50 year return period event); earthquake loading using the Uniform Building Code approach; and flood levels in drainage works (with return periods ranging from 1 in 2 years for culverts, up to 1 in 50 years for major flood control works).

The procedures employed by the Office of Disaster Preparedness and Emergency Management (ODPEM) were also examined. It was determined that ODPEM’s primary goals, of public education and emergency management, could be greatly enhanced by the acquisition of appropriately scaled mapping. This mapping should ideally be at a scale detailed enough to show infrastructure. Storm surge elevations for varying return periods should then be superimposed onto this base mapping.

Insurance industry practices and needs were then examined. It was assessed that in order to improve the risk quality of its insurance portfolios, it was essential for the industry to develop an in-depth knowledge of the contributors to this risk. Information that was considered to be important for this assessment included:

- Hazard mapping of threatened areas as a function of risk (such mapping should be done for hurricane winds, surges (i.e. flooding), earthquakes, etc.);
- Vulnerability of critical infrastructure, with the implementation of hazard mitigation measures and adherence to building code recommendations; and
- Adoption of sustainable criteria upon which to base recommendations for development.

The present regulations in Jamaica regarding set-back of infrastructure from the mean water line are presented in terms of foreshore slope and are not related to actual risk occurrence. The review carried out of the Town Planning Department regulations and practices clearly indicates the urgent need for revision of these setback regulations, to provide a clear linkage between setback limits and acceptable risk. One prerequisite for this type of approach is the adoption of an acceptable return period that will provide adequate protection against an acceptable level of risk. Recognizing this need, ***the suggestion has been put forward that the 1 in 25 year return period be adopted by the regulatory planning agencies***. Given the adoption of this level of risk, the computed surge elevation may then be drawn onto a suitably scaled base map. From this superposition, information may then be obtained regarding the vulnerability of infrastructure within the coastal zone. In addition, it has been recommended that the Town Planning Department maintain a mandatory minimum setback from the HWM, of 15 metres. This minimum setback is intended to incorporate safety considerations for both cliff-type shorelines and also for erosion considerations for beach-type shorelines.

Finally, as no appropriate code presently exists for the estimation of wave loading in the landward storm surge area, guidelines for the computation of wave heights at the shoreline have also been put forward.

Storm Surge Definitions

The actual components of storm surge have been defined as being the sum of three primary components:

1. Meteorological effects caused by the low atmospheric pressure at the center of a storm;
2. Wind effects caused by the wind stresses on the water surface; and
3. Wave effects caused by waves breaking in the surf zone (known as wave set-up).

These three components contribute to a static water level, which therefore does not include wave run-up, or the crest elevation of the wave above the mean water level. In addition, in the computation of storm surge, it is important to consider tidal variations and also long term sea level rise. For this latter component, a UNEP recommended rate of sea level rise of 5 mm/year is proposed.

Analysis and Presentation of Data

Once storm surge values have been computed for the long-term database, these must then be subjected to a suitable statistical analysis. From this analysis, it will be possible to estimate storm surge corresponding to a variety of return periods. Two statistical methods have been presented for handling hurricane/storm surge data. The first method is an *Annual Maximum Method*, which requires the computation of a maximum value of storm surge for each year of record. The second method is a *Peak Over Threshold Method*, which requires the identification of storms passing within a user-specified distance from the location of interest. Results from each method were found to be very similar for the more extreme events (e.g. over 1 in 25 years), but the Peak Over Threshold method resulted in higher value predictions for more frequent events.

The visual presentation of this data has been described in the report, and the following steps are proposed:

1. First, a base map must be prepared on which all generated data can be superimposed. This mapping is typically obtained either through the generation of ortho-rectified images, or through the use of geo-referenced Survey Department maps. Depending on the scale of mapping used, data pertaining to infrastructure location should be included.
2. The base map should contain topographic information, which may be in the form of land contours or spot elevations, or both.
3. The minimum requirements of appropriate mapping for storm surge delineation should be at a minimum scale of 1:5,000 with contour intervals of 1.0 metre for the first ten metres in elevation above datum.

4. The inclusion of land use data is strongly recommended. Data pertaining to land use zones may be obtained (in the case of Jamaica) from the Town Planning Department's 1993 Development Order.
5. The map should also contain enumeration data. This may be obtained, in the case of Jamaica, from the STATIN 1991 Census data, with the coastal zone data extracted.

Recommendations for Use/Application of Storm Surge Data

It is recommended that a rational approach to the regulation of setbacks should be implemented. These setbacks need to be based on actual statistical risk, in order to provide a consistent means of protection along an island's shoreline. The legal mechanism for this approach would be through Development Orders, which should include the demarcation of a flood line. The main drawback to the implementation of this approach pertains primarily to the requirement that storm surge data must first be generated for the entire coastal zone (in a lateral sense), and appropriate mapping (minimum scale of 1:5000) must be available.

Engineering considerations within this zone include the following:

- Flood proofing of structures including the placement of critical infrastructure above the predicted inundation level. Alternatively, flood proofing may be achieved by designing the ground floor of buildings to be dispensable during major surge events.
- Buildings that may be threatened by wave action within an inundation zone should be designed to withstand the forces resulting from the expected wave height at these locations. The Shore Protection Manual (USACE, 1984) contains the procedures for computing wave forces on structures.

Finally, for the proper application of emergency management procedures, it is essential for these agencies to have access to mapping showing maximum inundation limits corresponding to varying categories of storms (in accordance with the Saffir Simpson scale). This mapping may then be used to identify the most vulnerable infrastructure, and as well, to estimate the number of people who may be threatened by flooding, for a particular category of tropical storm or hurricane.

Results of Case Study

A case study was carried out for the Montego Bay area, and in particular at Doctors Cave. Computation of storm surge was carried out using both the TAOS model with an annual maxima approach, as well as the generic model, with a peak-over-threshold approach. These analyses gave the following results:

1. For the TAOS/Annual Maxima approach:

Montego Bay Storm Surge (m) using 2-Parameter Weibull Distribution (Doctors Cave)

Estimate/Confidence Limit	**Return Period (years)**			
	10	**25**	**50**	**100**
MLE	0.97	1.56	2.07	2.61
90% limit	1.15	1.90	2.56	3.28
95% limit	1.20	2.04	2.79	3.62
99% limit	1.34	2.28	3.11	4.06

2. For the Alternative/Peak-Over-Threshold approach:

Doctor's Cave Storm Surge (m) using Weibull Distribution k=1.4

Estimate/Confidence Limit	Return Period (years)			
	10	**25**	**50**	**100**
MLE	1.7	2.1	2.4	2.7
90% limit	1.9	2.4	2.8	3.1
95% limit	2.0	2.5	2.8	3.2
99% limit	2.0	2.6	3.0	3.3

Using the alternative approach, storm surge values for varying return periods were also computed for the Montego Bay Airport, the Montego River outfall and the Montego Freeport. The 1 in 25 year return period (MLE) surge computed at these locations were 1.6 m, 1.7 m and 2.5 m respectively, indicating a range of almost 1.0 metre depending on the exact location.

In the presentation of the computed data, a base map was prepared from 1:15,000 scale 1991 colour photography of the area. Ortho-rectification of these images was achieved by following a novel process, whereby the available data was used to produce a detailed base map image at a relatively low cost. The ortho-rectification process involved the following steps.

- Aerial photograph contact prints (at 1:15,000 scale) were scanned at 600 dpi resolution to create digital aerial imagery. Un-published Survey Department 1:2,500 maps were then scanned and geo-referenced.
- Plan control for scaling and orientation within the national grid was extracted from the 1:2,500 maps and vector elevation coverage. The digital aerial imagery was geo-referenced.
- Land elevation contours were digitized (heads up) from the raster maps, along with the elevation points shown on the ground, to create a digital vector coverage of the study area. This would facilitate the creation of a DEM for terrain relief correction.
- The digital aerial image was then ortho-rectified using pixel-by-pixel single frame techniques available in ERDAS IMAGINE 8.3 software. The individual frames were then re-sampled and a mosaic image created. The image base map and vector contour coverage was suitable for importing into ESRI ARCVIEW 3.1 software for GIS analysis.

The computed storm surge results for the case study have been mapped within a GIS, which has been used to evaluate infrastructure and population areas at risk. The coastal zone of the Montego Bay area is planned for resort, resort/residential, transportation, conservation, commercial/office, institutional, light industry, open space, public assembly, public buildings, agriculture and residential uses. Mapping of the 1 in 25 year return period surge (see Figure ES-1) indicates that of a total land area of 1400 hectares within this zone, approximately 480 hectares (or 34%) will be impacted by storm surge. In addition, it was found that land areas associated with conservation, resort and transportation (airport) were the most seriously affected.

The population within the coastal zone was obtained from the 1991 Census data, to be 16, 626. Significant growth of this number is not expected, since the area is already well developed and there is little provision for new housing other than through the redevelopment of existing housing lands. Mapping of the storm surge shows that the 1 in 25 year event will not have major impacts on this population. By contrast, the 1 in 50 year event is shown to have significantly more impact and would require mitigation planning by ODPEM. The physical problems likely to be experienced by these communities during the close passage of hurricanes are attributable to low level flooding and public health risks associated with contaminated water.

Finally, the mapping of storm surge showed that some critical infrastructure would be threatened during the passage of a storm (see Figure ES-2). These included: the new Divisional Police Station; the new main NWC sewage pump station; and the Sangster International Airport. Special emergency management plans will need to be formulated to ensure that as soon as the elevated waters subside, these facilities may be returned to active service. In addition, the banks of the North and South Gullies, and the Montego River, are likely to be overtopped, as elevated water levels at sea will affect the flood regimes in these watercourses.

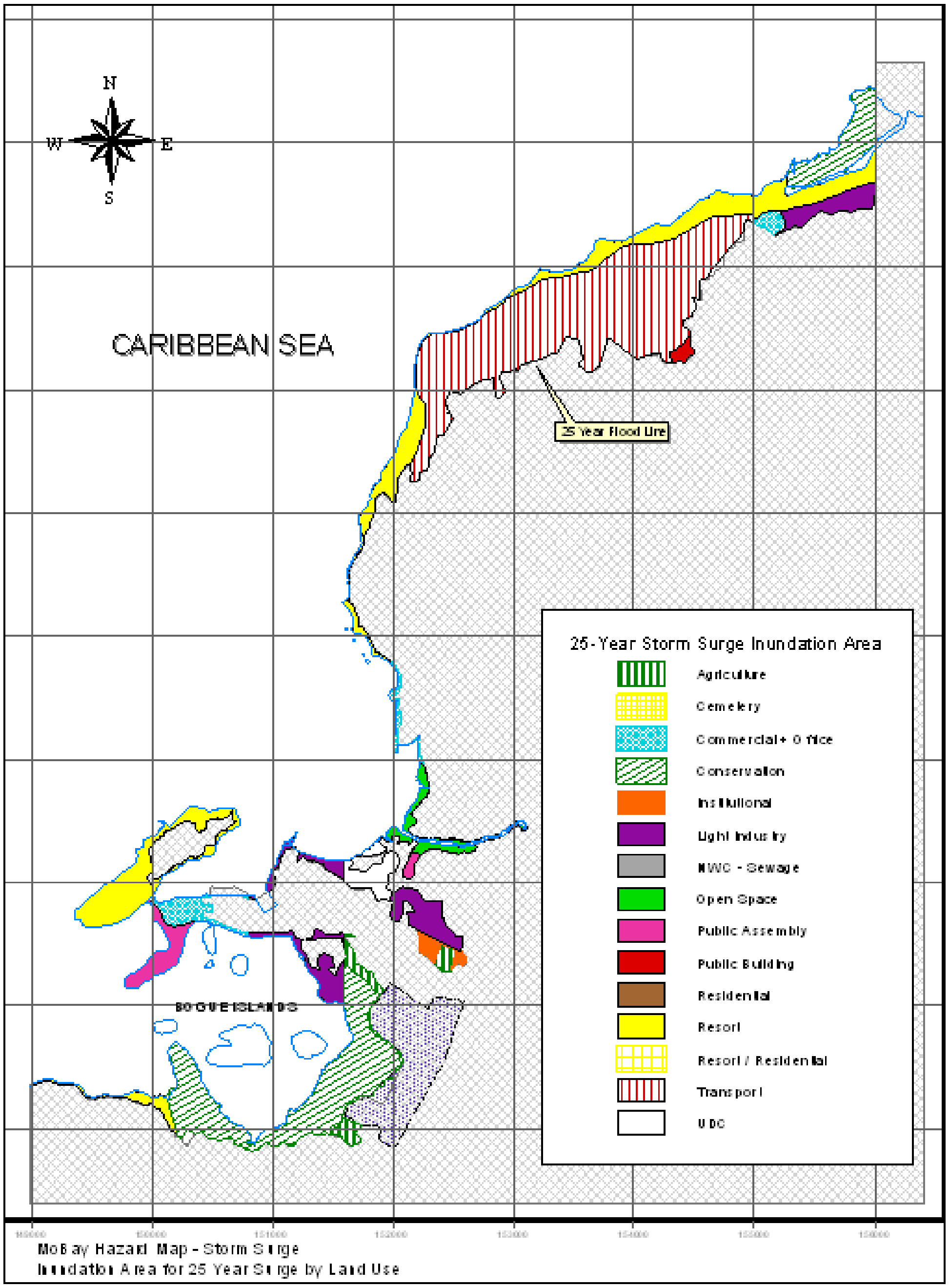


Figure ES-1. Inundation Area for the 1 in 25 Year Hurricane Surge

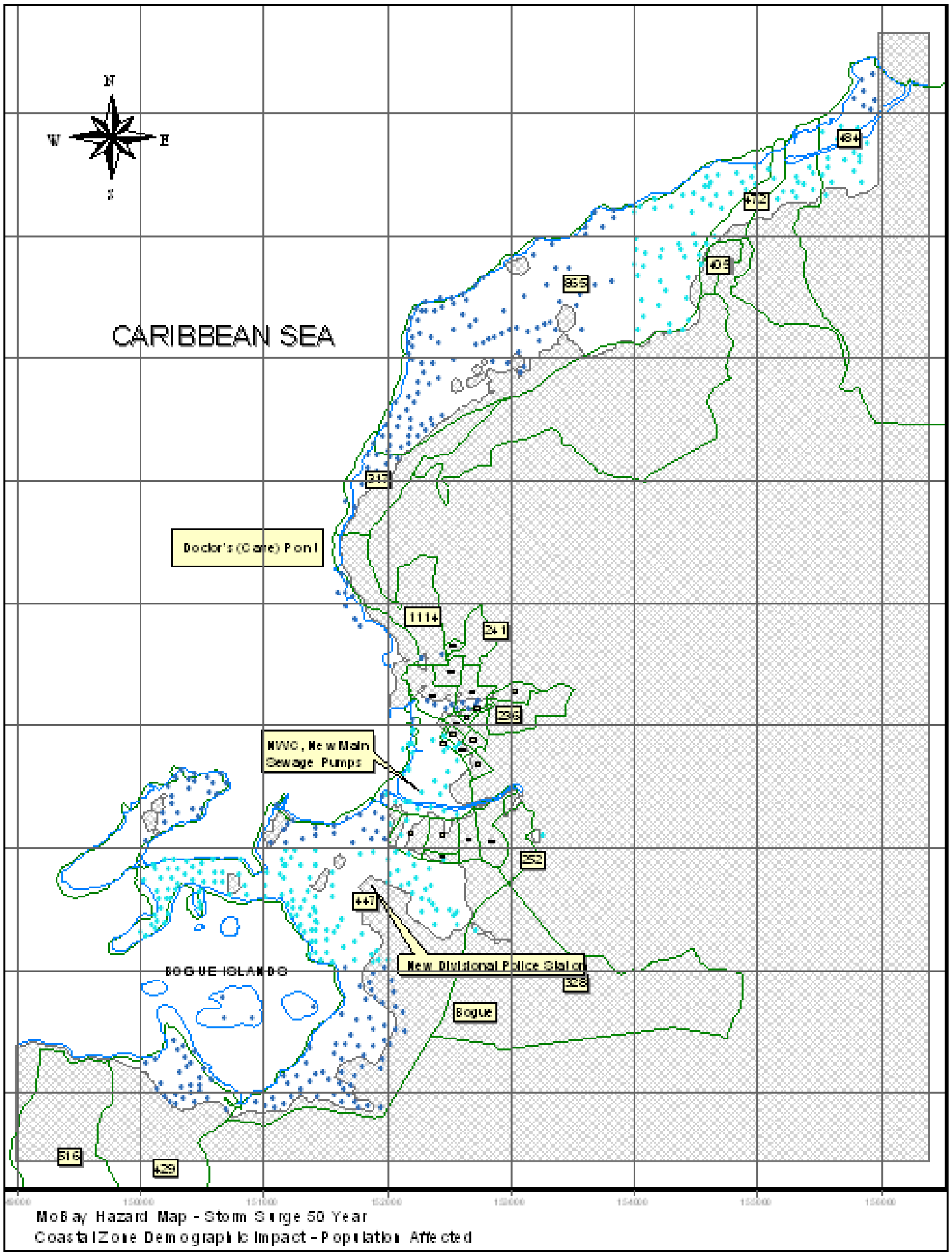


Figure ES-2. Impacts of Storm Surge on Population/Critical Infrastructure

Table of Contents

1. Introduction

From 1993 to 1999, the General Secretariat of the Organization of American States (OAS), in collaboration with the United States Agency for International Development (USAID), has been sponsoring the Caribbean Disaster Mitigation Project (CDMP). As part of the CDMP, a storm hazard pilot project was developed for Montego Bay. The intention and/or objective of the CDMP was that the results of this pilot project would be applied throughout the entire Caribbean region. One of the mandates of the CDMP was to develop maps showing flood levels resulting from hurricane-generated surges. In order to develop a usable and repeatable method of presenting the storm surge information, a case study was made for Doctor's Cave in Montego Bay (see Figure 1.1).

This document is a final report on the Montego Bay storm hazard project. Three main components are included in this report. The first is the recommendation for a policy framework, for the use of storm hazard information in Jamaica. In developing the policy framework, an assessment of the current practice regarding the use of any hazard information by planners, engineers, and the insurance industry has been made.

The second part of this report includes a set of guidelines for the computation, interpretation, use and presentation of storm hazard information. As part of these guidelines, some basic definitions for storm surge are made.

Finally, the third section gives a description of the case study that was undertaken for Doctor's Cave in Montego Bay. In this section, a description of the storm surge models used, are described. Also in this section is the presentation of a digital database of storm hazard information for the Montego Bay, pilot project area.

The report also includes a description of the entire project development, including papers presented at the October 1997 Technical Workshop (Appendix 1).

1.1 Background

The first series of storm hazard maps for Montego Bay were produced in 1994. These maps showed a line indicating the limit of surge and wave run-up ranging from +5.0 to +6.0 metres. A Saffir Simpson category 4 hurricane following a worst-case track was used as the "100 year storm".

Figure 1.1 - Nautical Chart of Montego Bay (BA Chart No. 468)

In 1995 storm surge computations were made for a number of incident storm conditions at Montego Bay. Storm surge elevations were predicted for hurricanes characterized within each group of the Saffir Simpson Scale, and with various directions of forward motion (North, West, and Southwest). Coming out of that initial analysis, a series of Maximum Envelope of Water (MEOW) generated surge maps were prepared. The predicted peak surge elevations at Doctors Cave for a Category V hurricane ranged up to 5.2 metres using this technique.

Subsequently, storm surge values were recomputed for the 10, 25, 50 and 100 year return period storms using a statistical approach. In this third analysis, the effect of different observed (i.e. actual) track directions was implicitly included in the computation of the surge. This latter approach led to the prediction of surge values that appeared to be more in line with anecdotal (historical) observations made in Montego Bay. Specifically, during the 1912 hurricane, water was observed to reach up to the Railway Station steps, an elevation of approximately +2.0 m above MSL.

The storm surge model that was used for all of these applications was the TAOS model, which is described in greater detail in Section 4. Following the calibration of this model in Montego Bay and at other locations throughout the Caribbean, it has been used extensively in Florida to delineate zones of potential flooding resulting from storm surge. In addition, the model has recently been used to predict storm surge values for the Kingston Metropolitan Area. For this application, the model has been run in a 2-dimensional (spatial) mode. In this way, values of storm surge are predicted at each model grid node, rather than at a discrete location, as was the case for the Montego Bay study.

In the interest of transparency, consistency and repeatability, the modeling approach taken was submitted to the Jamaica

Institution of Engineers (JIE) for review. This review process resulted in a number of queries being raised, regarding the correct approach to be taken in the computation of storm surge and in the appropriate determination of return period and risk. Specifically, the primary issues/queries that came out of that review process were:

1. The approach used in the first assessment in 1994 to develop storm surge return periods required modification, as it actually led to more severe return periods than were accounted for, or assumed. This was primarily as a result of the fact that for each category of hurricane considered (i.e. on the Saffir Simpson scale), only direct hits were simulated. Since the track of a hurricane is one of the variables that contributes significantly to surge height, this approach resulted in unrealistically high estimates of the surge values.
2. The overall statistical approach to the problem required some fine-tuning, in order to arrive at a sound methodology. Initially, the historical data was partitioned into groups of 25-year periods. This method was subsequently modified so that the entire historical record of storms was analyzed in one grouping.
3. The definition of storm surge, in terms of its constituent components, required formalization and ratification. During the early stage of the work, there were components of storm surge accounted for in the analysis that were subsequently excluded. These included components such as the height of the wave above the MSL and an allowance for wave run-up (a dynamic component of water levels). Following the review process, only the static components of storm surge were taken into account.

In the course of addressing these issues, a workshop was held in Kingston, Jamaica in October 1997. Presentations were made at this forum by a number of individuals who had been retained by the OAS to provide clarification to the overall issue of storm surge. These are included as Appendix 1 of this report.

First, Charles Watson, author of the TAOS model, made a presentation, during which the structure of the model and its components were described. In addition, the extent of the model storm database was outlined, as were some calibration efforts that had been carried out. Next, the statistical analysis performed on the model output (i.e. surge data) was described in detail by Professor Johnson of the University of Central Florida. Third, Professor Sorensen of Lehigh University, Pennsylvania presented a paper on the appropriate components that should be included in the computation of storm surge. Finally, a presentation was made by David Smith on the actual methods of computing these various storm surge components. During the workshop, the presenters and a panel that had been assembled fielded questions that were posed by members of the audience. Coming out of this workshop, agreement was reached as to the optimum method for finalizing the Montego Bay storm surge analysis and presentation. This included further input from Professors Johnson and Sorensen and a synthesis of all work done, leading to the final approach to storm surge computation. This document therefore forms the culmination of these varying inputs and, under the section for guidelines, presents a rational and sustainable method for calculating storm surge.

1.2 Terms of Reference

The OAS retained Smith Warner International (SWI) and Maurice Jones (MJ) to carry out the collation and synthesis of the data generated previously and to prepare a summary document outlining the correct method of estimating storm surge. Specifically, the following were the objectives of the contract, followed by the detailed Terms of Reference of the work to be carried out.

1.2.1 Objectives

The objectives of this consultancy are described following:

"To minimize the effects of natural hazards, it is critical to understand their characteristics at a given location. To this end, the Caribbean Disaster Mitigation Project (CDMP) developed storm surge information for Montego Bay, Jamaica. For appropriate use of this information in development planning and engineering studies, it is critical that the information be made available in an understandable format and with guidelines for its use. Under this contract, the storm surge information produced for Montego Bay will be mapped on an appropriate map base, and guidelines for use of any storm hazard information in development planning and engineering studies in Jamaica will be produced."

1.2.2 Specific Tasks

The Terms of Reference called for the carrying out of a number of specific tasks. These are summarized following.

1. Development of a base map of Montego Bay, through mosaicing and orthorectifying aerial photographs of the area.
2. Develop a policy framework for the use of storm hazard information in Jamaica, through discussions with appropriate agencies and organizations, including but not limited to the Jamaica Institute of Engineers (JIE), the Town Planning Department (TPD) and the Office of Disaster Preparedness and Emergency Management (ODPEM). This policy framework should be applicable to all storm hazard information, whether produced by the CDMP or others.
3. Development of guidelines for the use of storm hazard information for economic and physical planning and engineering in Jamaica. The guidelines will include discussions of the risk, delineation of hazard zones and standard terminology for use when discussing storm hazard information. These guidelines should be applicable to all storm hazard information, whether produced by the CDMP or others.
4. Prepare a digital database of the storm hazard information, superimposing the storm hazard information produced for Montego Bay upon the base map developed in Item 1 above. This digital database is to be designed in a format and on a platform that allows for public distribution (e.g. ArcExplorer).
5. Prepare a final report on the Montego Bay storm hazard project. This report should include a background to the project, copies of the technical papers presented at the October 1997 workshop on the Montego Bay project, the policy framework and guidelines described above (Items 2 and 3) and a description of the digital dataset (Item 4 above). This report should be in a format which can be distributed both as part of the digital database and independently. The report will include an Executive Summary, which can be distributed independently of the full report.

2. Policy Framework for Storm Hazard Analysis

During the passage of a hurricane, three main types of storm hazard are experienced. These included wind damage, inundation from elevated water levels (storm surge) and structural damage or erosion from wave action. While a policy framework must encompass all three of these hazards, this document deals primarily with storm surge. The development of a national policy framework for storm hazard analysis must be done in conjunction with other policy frameworks (e.g. Town Planning). It was therefore necessary to conduct a review of the current practices regarding the approach to risk and its regulation.

Following this review, a policy framework for Storm Surge Analysis is presented.

2.1 Current Practices & Regulatory Approach to Risk

This section of the report is an assessment of the current use of storm hazard information in design, regulation, emergency management, and insurance within Jamaica.

2.1.1 Jamaica Institution of Engineers (JIE)

Discussions were held with representatives from the JIE regarding the risk levels that are assumed or implied in current design practice. One of the findings that came out of those discussions was the fact that no one standard of risk is applied across the board to all aspects of structural design. This fact in itself is not necessarily problematic, as the same level of risk is not always appropriate for varying phenomena. Varying return periods (i.e. levels of risk adopted) should, however, bear some reference to the likelihood of structural failure or to the consequences of failure. In addition, there are no standards presently being applied within the Institute that include the effects of storm surge and/or wave action. In fact, these standards are now being developed.

For the case of wind loading on buildings, a reference velocity pressure is used that corresponds to the mean velocity pressure over open water at an (approximate) elevation of 10 metres, averaged over a period of approximately 10 minutes and with a return period of 1 in 50 years. Adoption of this criterion leads to a base design windspeed of 120 mph, with this value being factored to account for distance inland from the sea and variations in terrain. In addition, the importance of the building to be constructed (i.e. level of risk which may be tolerated) may also be accounted for by the application of a design factor. This level of risk adoption is compatible with that being used in some other areas of engineering design and allows for good resistance to destruction resulting from hurricane winds. The following Table 1 gives an indication of the chance of a design event being exceeded for a given combination of return period and expected project life.

Table 1. Risk that design event will be surpassed in life of structure (%)

Design Return Period (years)	Expected Project Life (years)				
	5	**10**	**20**	**50**	**100**
5	67	89	99	100	100
10	41	65	88	99	99
25	18	33	56	87	98
50	10	18	33	64	87
100	5	10	18	40	63

With respect to seismic risk, the present design approach calls for adoption of the Uniform Building Code (UBC), which categorizes varying locations in the world into Zones. An increasing Zone number implies a greater risk of more frequent and intense, earthquakes. For Jamaica, the UBC recommends Zone 3 in general, with the potential of a Zone 4 rating being applied to the Kingston Metropolitan area. Zones 3 and 4 correspond approximately to Richter magnitudes 5-6 and 6-7 respectively. The correlation between these Zone rankings and return period risk is not explicit. To properly develop this linkage, it is necessary to examine the historical records of earthquakes and to rank these in a statistical way. Because the design code gets around this by assigning a Zone ranking, engineers designing for earthquake loading do not develop their designs in the context of a return period event.

The Jamaica Institution of Engineers has also prepared a set of guidelines for the design of drainage works. The return periods applied depend on the use and type of particular drainage structure, but ranges from a minimum of 1 in 2 year return periods for gutters and culverts, up to a 1 in 10 year return period for principal drains. A return period greater than 1 in 10 years is recommended only when economic analysis of risk suggests it to be necessary. This latter approach has been used for major drainage and flood control works, where 50 and 100 year return periods are used.

2.1.2 Water Resources Authority

The Water Resources Authority has undertaken flood plain mapping for the Rio Cobre flood plain. The delineation of the flood plain was determined using a detailed analysis of the catchment area and by modeling using a HEC-2 approach. Essentially, the flood catchment characteristics were used, in conjunction with long-term rainfall gauge data, to compute flows in the river. Measured flows resulting from specific rainfall events were then used to calibrate the rainfall-runoff relationship (the database of measured flood flows for the Rio Cobre River extends over 30 years). Once this calibration was complete, then the rainfall records were used to predict varying return period flows. The HEC-2 model is then used to predict water surface elevations in the river for these varying return periods. Maps at a scale of 1:4000 were used to present the results for flood lines at 10, 25, 50, and 100 year return period intervals. Flooding analyses have been conducted for other catchments (e.g. Hope River) however, no proper base mapping exists for presentation of the results.

The methodology for determining the flood flows for specified return periods was based on an extremal type statistical analysis of the predicted or measured flows from gauging stations.

2.1.3 Office of Disaster Preparedness and Emergency Management (ODPEM)

Discussions were held with the Director and staff of ODPEM, regarding the way in which emergency planning and implementation is carried out, particularly as it pertains to flooding from storm surge. In effect, ODPEM does not presently have a defined method of computing inundation risk or set back limits. This organisation therefore relies on storm surge and setback information computed by other agencies or individuals in delineating zones that would be at risk during the passage of a major hurricane.

The mandate of ODPEM is, amongst other things, to educate the public about the types of natural hazards that can occur, what their effects can be and what steps should be taken to ensure safety. In the area of hurricane-induced hazards, ODPEM issues warnings in the event of a hurricane passing close to the island. It also relies on the Meteorological Service to issue advisories on sea state and identify low-lying areas that could be threatened by storm surge. In summary, however, ODPEM does not possess any detailed mapping of the coastal areas of Jamaica, which it uses to identify critical infrastructure, or general housing, that could be at risk during the passage of a hurricane.

Recently, a Sustainable Development Study for the South Coast of Jamaica was completed. The boundaries of this study stretch from Kingston in the east, to Savanna-la-Mar in the west. One of the outputs of this work was the division of this section of shoreline into three (3) littoral cells comprised of 81 reaches, each delineating a section of shoreline that is relatively uniform in character. For each reach, storm surge estimates have been computed for the 1 in 10, 25, 50 and 100 year return period hurricane events. It is anticipated that once this data is mapped to a suitable scale, then ODPEM will be able to use it to enhance its emergency planning and response strategies. In addition, it is anticipated that the TPD will be able to use this information to assist in a more rational setting of setback distances.

2.1.4 Insurance Industry Practice

In a general sense, two primary methods exist for addressing the impacts of natural disasters in the Caribbean. First, impacts of disasters may be reduced through the application of hazard mitigation and/or vulnerability reduction measures. Second, economic measures such as insurance may be adopted to finance the costs of rebuilding after such a disaster. Typically, insurance companies within the Caribbean limit their coverage of catastrophe risk to less than 15%, and pass the remaining 85% on to the reinsurance market. It is of interest to note that typically, reinsurance that is available to the Caribbean insurers from these foreign reinsurance companies is based on worldwide natural disaster experience, rather than region-specific experience.

In recent years the Caribbean has experienced a number of natural disasters. First, there have been several severe hurricanes, which have ravaged both the Eastern and the Western Caribbean. Examples of these include:

- Hurricane Gilbert in 1988, that caused widespread damage and devastation in Jamaica (49 people killed and over 800,000 affected). Direct damage as a result of this storm was estimated at US$956 million, with another US$230 million in indirect damage (losses in export and tourism earnings);
- Hurricanes Luis and Marilyn in 1995, which severely impacted the Leeward Islands. It is estimated that the damage from these two storms in St. Kitts, Antigua/Barbuda and Dominica totaled approximately US$580 million; and,
- Hurricane Mitch in 1998, which resulted in the loss of nearly 10,000 lives in Central America.

In addition to the threat from hurricanes, the region has seen significant volcanic activity. Of prominence in this category has been Soufriere in Montserrat, which resulted in extensive evacuation and resettlement, and Kick-em-Jenny, a submarine volcano just north of Grenada, which has the potential to cause significant tsunami waves in the Eastern Caribbean. The region has also experienced seismic activity, although no major earthquakes have occurred recently which have led to widespread devastation.

The relative frequency of these naturally occurring disasters point to the fact that insurers in the Caribbean would be well advised to quantify the exposure of their portfolios to this risk. This is also advisable since different areas within the region have differing levels of exposure to these disasters. Further, it is in the interest of the policyholders that the insurers be able to accurately quantify their true exposure to the reinsurers, thereby obtaining reinsurance protection at a reasonable cost. This objective is of importance, since the insurance market in the Caribbean has been proven to be very sensitive to the cost of premiums.

Typically, the insurance industry in the region has acknowledged the critical importance of hazard mitigation techniques, however, this has traditionally been viewed as a government function. Further, it is generally acknowledged that the implementation of properly designed hazard mitigation and vulnerability reduction plans are much more cost-effective than spending on reconstruction in the wake of a major natural disaster. It is considered important, therefore, that governments in the region spearhead the creation of hazard maps that are accessible to a wide range of interests, including planners, engineers, architects, utilities, etc. In addition, the creation of such maps should be carried out under a national strategy.

In the area of the application of economic measures as a mitigating strategy, there has been a move to organize self-insurance programs aimed at providing coverage and reducing costs. As an extension to this, there has been some interest in establishing regional reinsurance pools aimed at providing coverage in the event of natural disasters. The general aim of such programs would be to provide more affordable disaster insurance. These aims, however, must go hand in hand with the strategies outlined in the preceding paragraph.

In order to improve the risk quality of insurance portfolios, it is necessary for the industry to develop an in-depth knowledge of the characteristics of this risk and to have access to well researched risk criteria. Information that would go a long way towards the building of such an understanding would include:

- Hazard mapping of threatened areas as a function of risk. Such mapping should be done for hurricane winds, surges (i.e. flooding), earthquakes, etc.;
- Vulnerability of critical infrastructure, with the implementation of hazard mitigation measures and adherence to building code recommendations; and
- Adoption of sustainable criteria upon which to base recommendations for development.

The development and/or compilation of such data requires a significant use of resources and time. The generation of this data, however, is fundamental to any national strategy for hazard mitigation. Further, as stated previously, it is of utmost importance that a raised level of awareness be achieved among public and private sector interests. In the assessment of risk, it is important to note that the database on hurricanes is slightly greater than 100 years, whereas for earthquakes it is approximately 500 years. The extents of these databases determine the degree of accuracy that can be expected in predicting recurrence probabilities or return periods. Once the hazard information has been developed, it is important that this data be portrayed in a graphic manner, suitable for use by planning departments and emergency planning offices.

2.1.5 Summary of Current Practices

What clearly emerges from this review of current practices in Government, regulatory and engineering bodies and within the insurance industry, is the need for well-researched data and information on hurricane hazards (among other natural disasters). Further, it is imperative that if this information is to be properly used, it must be presented in a manner that is as descriptive as possible, for ease of use by planners and emergency management teams. The creation of hazard maps showing zones of potential inundation as a function of return period (risk allocation) therefore forms one of the fundamental tools in the development of a sound vulnerability-reduction strategy of any country.

2.2 Current Regulations Regarding Set-Back

The Town Planning Department in Jamaica regulates the proximity of development infrastructure to the High Water Line (HWL), through the use of a setback regulation. Presently, these setbacks are regulated based on variations in shoreline slope, a criterion that results in three different categories being stipulated. These are shown in Figure 2.1 (taken from TPD regulations) and are described in the following paragraphs.

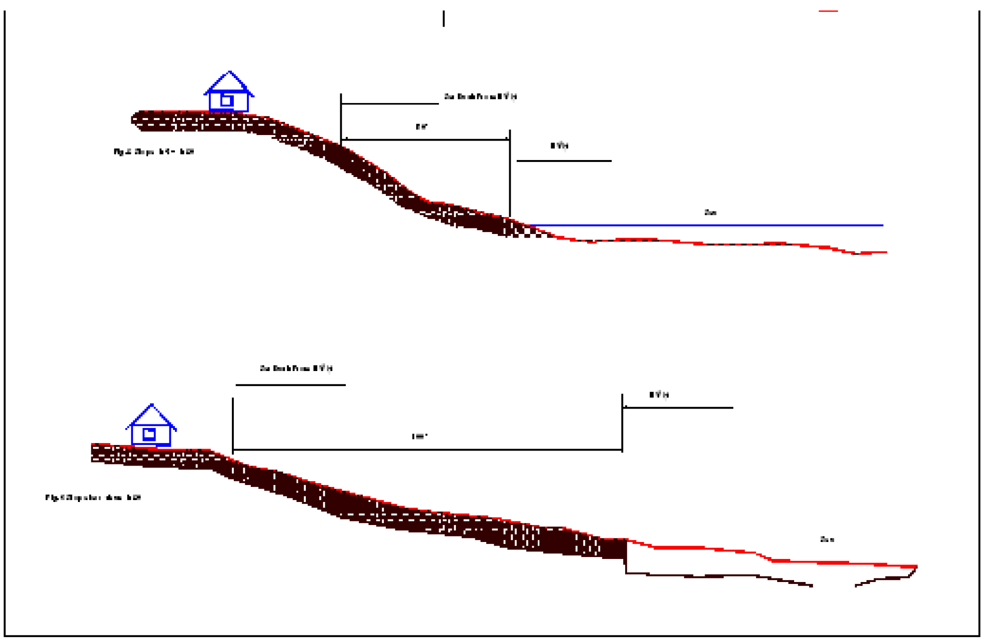
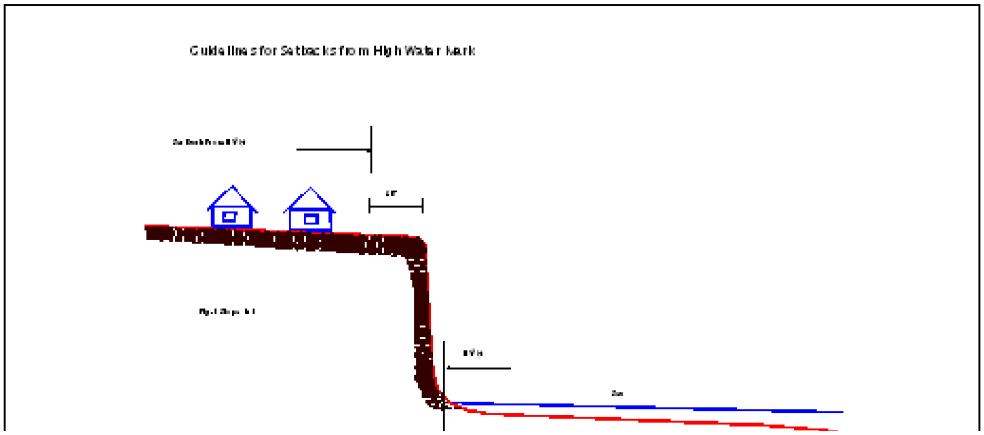


Figure 2.1 - Existing TPD Regulations for Set-back from HWL

The first category deals with shoreline slopes equal to or steeper than 1

(V):1(H) and calls for a setback of 7.6 m (25 ft) from the HWL for this category. Essentially, this criterion is relevant to cliff type shorelines and implies a backshore elevation of 7.6 m. This category therefore describes a shoreline that has good resistance to flooding from storm surge.



The second category deals with shorelines that slope at between 1:4 and 1:20. For this category, the setback required is 15.2 metres (50 ft). When specified on a 1:4 slope, this regulation implies a backshore elevation of 3.8 metres (12.5 ft). By contrast, at the other end of the range of slopes included in this category, a 1:20 slope implies a backshore elevation of 0.76 metres (2.5 ft). In terms of resistance to flooding, therefore, the shorelines included in this category could be expected to withstand surges ranging from approximately 0.8 – 3.8 metres above the HWL.

The final category deals with shoreline slopes less than 1:20 and specifies a setback distance of 30.5 metres (100 ft). This range of slopes implies a relevance to shorelines that have a backshore elevation of 1.5 metres (5 ft). For slopes more gentle than the 1:20 limit, the implied backshore elevation will be less than 1.5 metres. Figure 2.1 depicts the different slopes and the set-back distances.

From a review of these regulation criteria and through discussion with TPD personnel, it is clear that the TPD regulations pertaining to building setbacks need to be revised. As they presently stand, there is no link between these limits and implied risk factors. Further, it can be seen that each category has a different inherent resistance to risk from inundation. It is therefore strongly recommended that some consistency be introduced in the regulation of these setback limits, and that all shoreline types be managed in such a way that equal risk is assumed regardless of foreshore slope. In order to achieve this, it is necessary to first adopt a particular return period, which will provide adequate protection against an acceptable level of risk. This issue is discussed in further detail in subsequent sections of the report.

2.3 Recommended National Policy for Storm Surge Risk

A national policy for the computation and subsequent use of hazard information needs to be developed and implemented. In order to make the best use of limited resources, this policy must be based on a risk assessment of different hazards.

For design against wind damage, the present method for computation of loading is fully described in appropriate building codes. For storm surge, no such code presently exists. A rational, risk-based assessment of this parameter can be based on historical data, with this data being used to "recreate" surge elevations over the past 100 years. Statistical techniques can then be used to compute precise surge elevations for different return periods. Ideally, maps can then be used to identify areas that are at risk from storm surge. Depending on the detail of these maps, information may be obtained pertaining to the vulnerability of housing/buildings within the coastal strip. Within these zones, infrastructure development or activities must be regulated. Where such mapping has not been undertaken, a conservative surge elevation can be used.

Based on current practices regarding the treatment of risk, a minimum return period for the computation of storm surge, of 25 years, is recommended for adoption.

The current Town Planning Department regulations regarding set-backs from the high water mark should be modified to include the storm surge elevations, while maintaining a mandatory minimum set-back from HWM of 15 metres (50 feet), regardless of the slope of foreshore. This minimum set-back distance incorporates both a safety consideration for cliff-type shorelines as well as erosion considerations for beach-type shorelines. Other considerations may also be incorporated based on TPD objectives. These may include aesthetics, access, or the National Beach Policy.

Finally, for wave-induced damage, no appropriate code presently exists. It is recommended that at a minimum, design wave loading may be based on the limiting depth of water in which a wave may stand. Essentially, once the storm surge has been computed, then this data should be combined with the topographic terrain data to indicate the anticipated depth of water at the location of structure to be designed. The design wave height at this location should then be taken as being 80% of the mean water depth at the structure. This is the maximum wave height that will be able to exist in that particular depth of water. This wave height should be used to compute wave loading and should not be added to the previously computed storm surge.

3. Guidelines for Computation and Use of Storm Surge

One of the devastating impacts of the passage of a hurricane on a coastline is due to the occurrence of storm surge. This phenomenon is characterized by an increase in the mean water level above that ordinarily associated with tidal action. The computation of storm surge first requires a definition that can be agreed upon. Several methods presently exist for the computation and presentation of storm surge, depending on the available resources, including mapping. One such method, using the TAOS model, is presented in Section 4, along with another approach, which has been used as an independent verification. Following the computation of storm surge elevations, guidelines for the use of these storm surge values for physical/economic planning and engineering considerations are presented.

3.1 Definition of Storm Surge

Storm surge is itself caused by a number of interactions between the hurricane, the water body over which it passes, and the nearby land masses. Storm surge can be considered as the sum of three primary components:

1. meteorological effects caused by the low atmospheric pressure at the center of the storm;
2. wind effects caused by the wind stresses on the water surface; and
3. wave effects caused by waves breaking in the surf zone (known as wave set-up).

It should be noted that storm surge refers to a static water level, and as such does not include wave runup, or the elevation of the wave crest above the mean water level caused by the surge. These latter two phenomena are dynamic and are not usually included in the definition of storm surge.

In the computation of the storm surge components, it is also necessary to consider the normal range of tidal fluctuations that occur. Because hurricanes are generally slow moving systems, their storm surge effects may occur at any stage of the tide. Finally, the impact of long-term sea level rise should also be considered, as this will result in an increase in the elevation of the starting datum on which storm surge must be computed. More detailed descriptions of the various storm surge components are given in the following sub-sections.

3.1.1 Meteorological Effects: Inverse Barometer Rise (IBR)

The increase in water level under the low pressure "eye" of a hurricane is known as the Inverse Barometer Rise (IBR) effect. The increase due to this phenomenon is concentric under the center of the storm. The IBR can be calculated using a 2-dimensional model that assumes no flow normal to the shoreline, instantaneous water level response to the driving forces, and a uniform sea surface. The prediction relationship assumes an exponential reduction of atmospheric pressure radially outward from the eye of the hurricane. It is given by:

$$\Delta h = 0.1(P_n - P_o)\left(1 - e^{-R/r}\right)$$ (*Shore Protection Manual*, 1984) .... (1)

Where:

Δh = IBR (metres)
P_n = Ambient Pressure (kPa)

P_o'' = Pressure in "eye" of the hurricane (kPa)
R = Radius to maximum winds (km)
R = Radius to a particular location (km)

3.1.2 Meteorological Effects: Wind Set-up

The increase in the mean water level due to wind effects can be characterized in two ways. First, for enclosed bays, this component is primarily due to the piling up of water on the shore as a result of the non-rotating component of the hurricane wind. Typically, this effect can be broken into two components, the first being alongshore and the second onshore. It is the effect of the onshore component that leads to the wind set-up. Wind set-up can be computed according to the following one-dimensional analysis.

$$\Delta s = \frac{KW^2F}{d} \quad \text{(SPM, 1977)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Where:

Δs = Wind set-up
K = an empirical constant
W = Wind speed
F = Fetch length
D = Water depth

Second, for open coasts, the wind set-up is primarily due to the rotational component of the hurricane wind field. This set-up component results from the mean water level increasing in order to conserve the absolute vorticity of the storm system that exists in deeper water. As the storm approaches land, the water depths decrease and the frictional effects within the water column (Ekmann spiral) are contracted vertically. In order for absolute vorticity to be conserved, a lateral expansion (or divergence) of the water column is required. Since the drag caused by bottom friction reduces the total vorticity in the water column, it also reduces the divergence in the lower layers. Therefore, as the water depth decreases, it becomes difficult for the divergence in the lower layers to match the divergence in the surface layers. In addition, as the effect occurs closer to shore, the conservation of absolute vorticity in the water column becomes harder to achieve. The result of these interactions is a raising of the water surface, which is termed wind set-up.

It should be noted that larger values of wind surge are experienced at coastlines that have a wide coastal shelf (i.e. east coast of the USA), compared to those that have a narrow shelf (i.e. west coast of Dominica).

Wind set-up is best computed using a 2-dimensional hydrodynamic model, however, useful approximations may be obtained through the use of the 1-dimensional algorithm presented in Equation (2) above.

3.1.3 Wave Effects: Wave Set-up

The two primary effects that occur as a result of wave action under a hurricane are wave set-up and wave run-up. Of these, wave set-up is considered as being static, whereas wave run-up is dynamic. Wave set-up is a rise in the mean sea level, which is due to mass transport and the transfer of wave energy from a kinetic to a potential state. This phenomenon occurs within the wave breaker zone (or surf zone). Essentially, once waves begin to break, at the offshore end of the surf zone, a lowering of the mean water level occurs. This is known as wave set-down. Further into the surf zone, this effect is followed by a wave set-up, which reaches a maximum at the shoreline and which is typically an order of magnitude greater than the wave set-down effect.

Assuming a frictionless planar beach, Battjes (1974) developed the following equation to define average maximum wave set-up $(\overline{\eta}_{max})$:

$$\overline{\eta}_{max} = \frac{5}{16}\gamma_b H_b \approx \frac{H_b}{4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where:

γ_b = ratio of breaker height to water depth, and

H_b = breaking wave height.

The calculation of wave set-up may also be achieved using more advanced techniques such as the work of Battjes and Stive (1985), which includes the effects of friction and uses random waves. In this method, deep water (hurricane) waves are shoaled through the surf zone and the calculation of wave set-up is carried out to the point on the shoreline profile where the program calculates that all waves in the incoming wave train are broken.

3.2 Tidal Variations

Tides may be either diurnal or semi-diurnal in nature, meaning that a specific shoreline location may experience either one high and one low water per day, or two. For the sake of conservatism, it is recommended that storm surge be calculated at mean high tide.

3.3 Long Term Sea Level Rise

The impact of long-term sea level rise should be included in the prediction of storm surge, particularly where planning horizons of 25 to 100 years are being considered. The effect of this parameter will be to slowly increase the datum upon which the surge is to be computed. In calculating this parameter, both tectonic movement and actual long-term sea level rise should be considered. Usually tectonic movement is small compared to sea level rise.

Sea level rise may be estimated from an analysis of geological data such as old coral reef locations both on and offshore. More recent movements of sea level require historical tide gauge records for proper evaluation.

For future trends, and to allow for a possible "greenhouse effect' component, UNEP has predicted a rate for the Caribbean, of 5 mm/yr. Although somewhat conservative, it is recommended that this be figure be adopted until more site-specific, long-term water level data is obtained.

3.4 Statistical Methodology for Risk Assessment

Essentially, two components are necessary to the understanding of risk associated with a disastrous event. These are the magnitude of the event and the likelihood of its occurrence. Coming out of user feedback and through the review process carried out by the JIE, the CDMP has adopted an approach for estimating the maximum storm surge for a location, for various return period (e.g. 10-year or 25-year) events. In this approach, the storm surge model, e.g. TAOS, is run for all of the storms in the National Hurricane Center (NHC) database. From these model runs, annual maximum surge (or wind speed) values are extracted and then fitted to a statistical distribution curve. From the resulting curve, it is possible to estimate surges (or wind speeds) for any desired return period. The steps involved in this statistical analysis (from Johnson, 1997) are as follows:

1. Input the historical storm information, from the NHC database, to the model.
2. Run the storm surge model for each storm in the data set and record the observed storm surge at the selected site.
3. For each year in the historical database, select the maximum observed storm surge level (or maximum wind speed) from all of the storms that occurred that year.
4. Fit an appropriate statistical distribution to the annual maximum values.
5. From the fitted distribution curve, estimate the storm surge (or wind speed) associated with the return period of interest.
6. Compare the fitted distribution to the empirical distribution to determine the uncertainty in the estimate calculated above.

This approach, though tedious, is recommended since it ensures that there are no missing years of data from the statistical simulation (there will obviously be certain years during which there will be a very small or negligible storm surge), thereby increasing the accuracy of the prediction. Further, it produces realistic estimates of storm surge, which will be relevant to the point, or shoreline of interest.

Alternative statistical approaches may, however, be used provided that the inherent definition of storm surge, return periods, and risk are consistent. Such an alternative statistical approach is the use of a "peak-over-threshold" analysis, which, unlike the annual maxima, conducts its analysis from the number of events in a given duration that exceed some particular value. One way in which this method has been applied, has been to search the 100+ years of hurricane records, to extract data for only those that have passed within a given distance of the location under consideration and then to compute the storm surge for these. In effect, this method screens out lower values of storm surge that may be caused by storms that are sufficiently far away from the site under consideration. In addition, this method allows for the inclusion of more than one storm per year in the statistical analysis. At this point, an appropriate statistical distribution can be fit to the data and estimates of storm surge as a function of return period can be derived.

It is useful to note that in using historical records to estimate future events, a number of assumptions must be made:

1. Future storms will be similar to past storms.
2. The quality of information contained in the historical storm data set is consistent.
3. There are no meteorological trends in storm generation.

Work carried out in the Eastern Caribbean, and also for Jamaica, has indicated that there could be a trend towards an increase in "storminess" (Halcrow 1998). Specifically, it was found that the average significant wave height resulting from storm systems has increased since the start of record keeping. Figure 3.1 shows the percentage of wave height data that is greater than a given threshold level, as a function of time. The blue line in this diagram gives the percentage increase in wave height data above a 2 m wave height threshold, while the black line gives the same data but with a 3 m wave height threshold. The results show that between 1955 and 1995, the percentage of wave height data over a 2 m threshold, observed in the Eastern Caribbean, has increased from 11% to 55%. Similarly, for the 3 m threshold, the wave height data has increased from 2% to 20%.

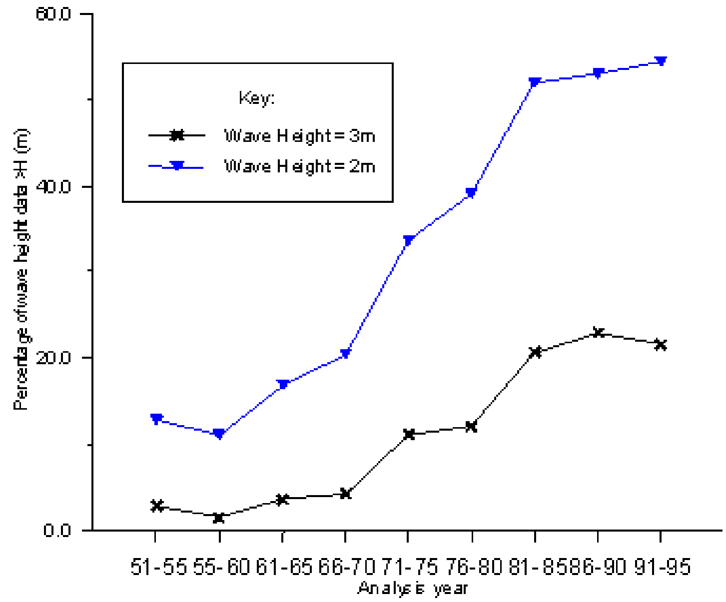


Figure 3.1 Increase in Wave Heights, Eastern Caribbean (Halcrow, 1998)

The other point that is worthy of note is that the quality of information collected by the NHC increased significantly after the 1950's. Despite these violations to the inherent assumptions related to this analysis, the statistical method described here is nevertheless recommended as being perhaps the best approach currently used for estimating the return periods of storm surge.

Surge height estimates derived from fitting the computed surge data to an appropriate statistical distribution, result typically in a maximum likelihood estimate (MLE) of surge for each return period considered. This is the statistical value that is most commonly used in engineering practice. For critical or high-risk infrastructure, it may be appropriate to circumvent the uncertainty in the input data by using a more stringent confidence limit from the selected distribution. For example, it may be prudent to use 90 or 95% confidence limit values, to ensure that the risk of the design event being exceeded is reduced. Conversely, it is also possible to apply a more stringent return period criterion (for example, use of a 1 in 100 year event instead of a 1 in 25 year event).

3.5 Mapping Guidelines

In order to enhance the presentation of storm surge data and to facilitate its use by regulatory agencies, planning departments and engineering offices, it is important that the hazard data be presented in a consistent and clear manner. Following are some guidelines for the data that should be contained in such mapping.

1. First, a base map should be prepared on which all generated data can be superimposed. This mapping is typically obtained either through the generation of ortho-rectified images, or through the use of geo-referenced Survey Department maps. Depending on the scale of mapping used, data pertaining to infrastructure location should be included.
2. The base map should contain topographic information, which may be in the form of land contours or spot elevations, or both.
3. The minimum requirements of appropriate mapping for storm surge delineation should be at a minimum scale of 1:5,000 with contour intervals of 1.0 metre for the first ten metres in elevation above datum.
4. The inclusion of land use data is strongly recommended. Data pertaining to land use zones may be obtained (in the case of Jamaica) from the Town Planning Department's 1993 Development Order.
5. The map should also contain enumeration data. This may be obtained (in the case of Jamaica) from the STATIN 1991 Census data, with the coastal zone data extracted.

3.6 Recommendations for Use and/or Application of Storm Surge Data

3.6.1 General Comments on Existing Regulations/Practices

The main conclusion from the review of existing regulation practices was that a rational approach should be adopted. While the current approach regarding setbacks provides some level of protection, a rational approach, which takes acceptable risk into consideration, is a more justifiable approach.

The legal mechanism for adopting this more rational approach would be through Development Orders, which should include the demarcation of a flood line. The demarcation of a flood line requires that storm surge analyses be undertaken for the entire island, starting with the major urban areas. For such maps to be created, suitable base mapping must also be available and/or created.

3.6.2 Guidelines for Planning Application

The use of a rational, risk-based approach to town and country planning is strongly recommended. At the present time, current provisions for regulating set-back from the High Water Level, as it relates to storm surge, are not based on a rational approach. The main advantage of a rational approach is that zones that have a storm surge risk can be easily identified and activities within these zones can be regulated. It is therefore recommended that the establishment of a development set-back based on actual statistical risk and providing a consistent means of protection, now be implemented.

This recommended approach does, however, have some implicit difficulties. Primarily, in order to establish set-back regulation data for the entire coastal zone, it is necessary that storm surge data be generated for the return period to be adopted. Mapping of appropriate planimetric and topographic data (to a minimum scale of 1:5000) will also be required.

The planning regulations should also relate to engineering considerations, such as flood-proofing, as well as to emergency planning measures.

3.6.3 Guidelines for Engineering Application

Engineering considerations within the regulated surge zone should address the following issues:

- Flood proofing of structures that fall within a threatened zone. Such flood proofing may include the placement of critical infrastructure above the predicted inundation level, or may be achieved by designing the ground floor of buildings to be dispensable during major surge events.
- The design wave height at any location within the inundation zone should then be taken as being 80% of the mean

water depth at the structure. This is the maximum wave height that will be able to exist in that particular depth of water.

- Buildings that may be threatened by wave action within an inundation zone should be designed to withstand the forces resulting from the expected wave height at these locations. The Shore Protection Manual (USACE, 1984) contains the procedures for computing wave forces on structures, which can be summarized as follows:

Dynamic Pressure: $p_m = 0.5$ w d_b (4)

where:

w the unit weight of water
d_b the water depth of the breaking wave height, which can be computed as follows:

d_b = 1.8 x (Design Surge Height - Ground Elevation + Erosion Allowance) .... (5)

where: Erosion Allowance depends on soil conditions and exposure, but should be a minimum of 0.15 metres up to 1.5 metres for sandy soils close to the shoreline.

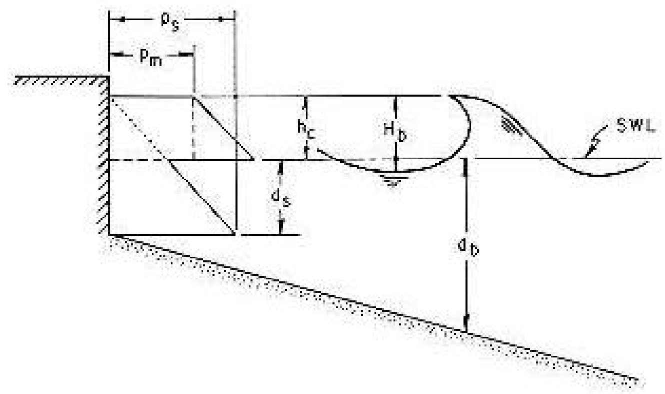


Figure 3.2 - Wave Forces on Vertical Wall (USACE, SPM, 1984)

The hydrostatic pressure will vary from zero at the height 0.8 d_b above the surge elevation to a maximum at the base of the wall equal to:

Static Pressure: $p_s = 1.6$ w d_b .... (6)

3.6.4 Guidelines for Emergency Management Application

Emergency management procedures described in Section 2 indicate that ODPEM relies on the Meteorological Services to issue advisories on tropical storm activity. In order to interpret these advisories, maps showing maximum inundation limits for different categories of storms according to the Saffir Simpson scale need to be available. Once appropriate mapping has been developed, this data may be used by Emergency Management Agencies to develop suitable strategies in the event of a major hurricane storm surge. Assuming that sufficiently detailed mapping has been obtained, then it will be possible to identify the most vulnerable infrastructure, as well as to estimate the number of people that will be threatened by flooding, for a particular return period storm. Armed with this knowledge beforehand, it will then be possible (given advance warning of hurricane track and intensity) to develop a strategy for the rapid evacuation of people in areas that are identified as being most vulnerable to storm surge inundation.

As an improvement to the use of the maximum inundation limit maps, forecasts of predicted storm surge elevations can also be made. The National Hurricane Centre in Florida, amongst others, make 6 hour, 12 hour, 24 hour, 48 hour and 72 hour predictions of storm track and intensity. Using this information as input to a storm surge model such as TAOS/L would guide emergency managers to appropriate use of resources.

4. Case Study – Montego Bay

4.1 General

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In order to ensure that the storm surge algorithms were set up properly and were representative of the actual physical processes, a case study was undertaken for Montego Bay. In particular, storm surge was computed for Doctors Cave on the Montego Bay shoreline. The case study involved the following steps:

- Prediction of storm surge elevations (at Doctors Cave) using the TAOS model.
- Verification of the TAOS model results using an alternative method of storm surge prediction (surge elevations computed at Doctors Cave and at three other locations along the Montego bay Shoreline).
- Comparison of the storm surge results with historical, anecdotal information.
- Mapping of the results in a GIS.
- Applications of the mapped results.

The following sub-sections describe these steps in some detail, and outline the ways in which this type of hazard data may be used by planning departments and emergency management agencies.

4.2 Existing Regulatory Set-Backs

The existing regulations presently in use in the Montego bay area by the primary planning and development agencies, governing the requirements for set-back of buildings from the water line, are summarized following:

1. *The Town Planning Department* regulates development in the study area by a statute "The St. James Development Order – 1983". The primary provision in the law for the protection of the community with respect to high water levels associated with storm surge, is a set-back provision which varies between 25 and 100 feet from the **High Water Line** (HWL), depending on the features of the shoreline.
2. *The Urban Development Corporation (UDC)* has had responsibility for many major development initiatives in the study area. The UDC has adopted 7 feet (2.13 metres) above **Mean Sea Level** (MSL) as the minimum floor level for most if not all of its developments, based on site-specific storm surge studies and risk evaluations done over 25 years ago. This decision has served Montego Bay well as it has provided a rational basis for the protection of the community.

4.3 Computation of Storm Surge – TAOS Model

4.3.1 Overview Description of TAOS Storm Surge Model

Recognizing that the Caribbean region has been prone to severe annual damage from hurricane attack, the USAID/OAS Caribbean Disaster Mitigation Project (CDMP) has promoted the development of the TAOS/L model. This computer model is specifically a storm hazard model that was originally set up for use in the Caribbean. Its primary use has been to quantify the impact of storm surge on coastal areas throughout the region. The model was developed by Charles Watson for the Caribbean Disaster Mitigation Project, based on a generic model first applied to Hilton Head, South Carolina. It is a PC-based numerical model that produces estimates of maximum sustained winds at the water surface, along with still water surge height at the coastline. The model has been set up to incorporate all of the storms in the US National Hurricane Center (NHC) database and models the entire Caribbean basin. Model runs can be made for any historical storm, for probable maximum events associated with different return periods, or using real-time tropical storm forecasts from the NHC.

The TAOS/L model is well suited for storm hazard modeling in the Caribbean, and may be particularly useful for regulatory or emergency management agencies that need to have access to this type of information. In its current format, use of this model is facilitated in a relatively easy manner by limited training of qualified staff. Although it is recommended that operators of the model have an understanding of the physical components that go to make up storm surge, it is not necessary for the physics of these processes to be known. Recently, training of personnel in the use of the model was undertaken, with participants from Belize, Jamaica, Mexico and Barbados being involved in this training exercise.

Some advantages of the TAOS model include:

- *Integration of wind and storm surge hazards.* Damage from storm winds is a significant factor in the Caribbean, yet this factor is rarely included in storm hazard models. The model can incorporate this hazard, but to do so, it must have as input fairly detailed topographic information that can be represented in a Digital Terrain Model (DTM) format.
- *Inclusion and use of a database of historical storms from 1886 to the present for the region.* As mentioned above, the model incorporates the full database of storms from the NHC. This database can be used to display paths of historical storms or as the basis for model runs.
- *It can be run on a personal computer platform.* The model can be set up to give predictions on a PC platform. This greatly expands the potential user base for the model.
- *The model has been set up to run for any location in the Caribbean.* TAOS/L includes the necessary input databases—topography and land cover—for the entire Caribbean. Therefore, in general no database development is required to run the model.
- *It produces GIS-compatible results.* The model results can be displayed automatically using a display program that is distributed with TAOS. Conversely, it may be imported into an external geographic information system (GIS) package. When incorporated into a GIS program, the storm surge predictions may be combined with detailed topographic mapping to illustrate what infrastructure could be threatened in the event of predicted inundation levels being reached. This information may either then be used by emergency management teams to formulate resettlement plans, in the event of a hurricane, or may be used by regulatory agencies to restrict development (or to input to building codes) in these threatened areas.
- *The model is run using a graphical user interface.* The model is controlled through an easily navigated menu interface.

4.3.2 TAOS Model Outputs

The model offers several different types of output depending on the intended use of the storm data. The primary application is an estimation of the effects of an individual storm on an island or a specific length of coastline. For this type of application, TAOS/L is able to model the effects of actual historical storms, hypothetical storms (created by the user) or currently active storms (using information from NHC advisories and forecasts).

The model results for these individual storm runs may be displayed in the form of maps, or as a time series. The maps display the maximum storm surge and wind speed that is predicted at the shoreline of interest, over the course of the storm. By contrast, the time series presentation gives the storm surge predictions at a point of interest along the shoreline and at regular intervals of time throughout the passage of the storm.

This type of output is very useful in developing an understanding of maximum likely storm surge at a shoreline of interest for a specific storm. This use of the model is probably of most interest from a forecasting perspective. In this way, it may be used by weather service bureaus to give flooding advisories

The second type of output that is available with the TAOS model is a maximum envelope of water or wind (MEOW). This type of output displays the maximum water level (or wind speed) generated by a storm of a selected intensity, forward speed and track. MEOWs may be produced by running the model for varying user specified storm tracks, each having the same selected intensity, speed and direction. The results of these runs are then combined to give the maximum storm surge at each point of interest. MEOWs should be prepared in advance of an actual storm, showing various combinations of storm direction, forward speed and intensity. For a storm that is approaching a particular shoreline, the MEOWs may be consulted and a predicted storm track, similar to the approaching actual track, selected. In this way, a good estimate of the potential maximum storm surge at a project shoreline can be developed, for an approaching storm. This type of information, while in most cases giving an overestimate of the storm surge that would actually be achieved, is of much use to emergency planning organizations. It is expected that these data and predictions can be used to develop advance warning and evacuation plans before the actual advent of the storm.

Finally, a statistical analysis of model ouptuts (see section 3.4) has been used to develop water levels, wind speeds, and wave heights for different recurrence probabilities (i.e. return period probabilities). A Caribbean-wide database was developed, which provides maximum likely estimates for wind speed, wave and surge heights for different return periods, for each point on a 1 km grid. This type of information is of most value to regulatory planning agencies and to engineers and architects who are involved with development projects close to the shoreline. It must be remembered, that the wave height output is valid only for deep water. For information on wave heights close to the shoreline, the deep water waves must be put through a refraction and shoaling process.

The primary limitation of these statistical outputs of the TAOS model is the fact that bathymetry in the nearshore zone is usually not well represented. This is as a result of the grid size that had to be adopted for Caribbean-wide modeling of storm surge. It is therefore recommended that prior to use in each Caribbean country, detailed nearshore bathymetry should be added to the bathymetric database of the model, to yield more accurate results.

4.3.3 Verification of TAOS Model

At the 17th meeting of the World Meteorological Organization's Region IV in Guadeloupe in April 1995, it was decided that the National Oceanographic and Atmospheric Administration (NOAA) would undertake a comparison of three storm surge models: TAOS, SLOSH and a French model. Following this comparison exercise, NOAA concluded that all three models produced "reasonable" forecasts that were relatively consistent with observations from actual storms.

In order to achieve further validation of the model outputs from TAOS, the model has been evaluated on over 25 historical storms from around the world. A comparison of over 500 peak surge observations with TAOS model estimates, gave results that were within 0.3 m for 80 percent of the time, and less than 0.6 m for 90 percent of the time [Watson 1995].

4.3.4 Model Applications

The TAOS model has been used at a number of locations throughout the Caribbean. These include:

- storm surge and inland flood hazards study of Parham Harbor, Antigua in 1995;
- an assessment of coastal surge and inland wind hazards in Belize, in 1996;
- an assessment of storm surge and wave effects on the west coast of Dominica (also in 1996) as part of a Caribbean Development Bank-funded coastal rehabilitation project,
- storm surges in Montego Bay (1994-1998), and
- wind and storm surge hazards in the Kingston Metropolitan Area (1999).

In particular, the Montego Bay simulations have served as a pilot for the overall project to develop the correct procedure for analyzing and interpreting the predicted surge data. The simulations carried out for each country are summarized following (OAS, 1998):

Antigua—Parham Harbor

The use of the model in Antigua was to provide support for a Tourism Infrastructure Upgrading Project. Under this project, historical storm return periods were developed and a series of storm surge maps were created. Only westerly storm tracks were used in the storm surge modeling, to reflect the historical observations that storms passing Antigua are almost all from this direction.

Belize

For this application, a return period analysis and storm surge mapping project was carried out for the coast of Belize. East of Belize, a shallow offshore shelf characterizes the coastal area. The occurrence of this shelf results in the entire shoreline being at high risk from storm surge damage. Part of this study investigated the variability of return period events along the coast. In summary, the geographic location of Belize in the Atlantic Basin and the geometry of the Gulf of Honduras and Central America, results in a strong north/south gradient to the occurrences of storms, with storms occurring more frequently in the north.

Dominica

During the first half of September 1995, two hurricanes, Luis and Marilyn, caused significant damage in the eastern Caribbean. In Dominica, a number of coastal defenses were destroyed along the west coast of the island. As part of a project to rebuild the damaged coastal infrastructure, the CDMP undertook a storm surge and wave hazard assessment in 1996 to ensure that the rehabilitation designs would be adequate to withstand future storms. Representative storms with return periods of 5, 10, 25 and 50 years were selected and modeled using TAOS and corresponding estimates for storm surge and wave height were produced. The models results indicated good uniformity in the predicted surge along the entire stretch of modeled shoreline.

Jamaica—Montego Bay

Since 1994, CDMP has undertaken three storm hazard assessment activities in Montego Bay. These assessments have been undertaken in coordination with the Jamaica Office of Disaster Preparedness and Emergency Management (ODPEM) and the Jamaica Institute of Engineers (JIE). The purpose of each of the three assessments was to produce valid maps of hurricane storm surge hazards for use in emergency management and land development planning for Montego Bay. The TAOS model was used for all three studies. The primary difference between the studies was in the selection of return period for use in modeling. In addition, refinements were made to the model and the analysis approach to reflect a better appreciation for the components that should be included in the storm surge analysis and a more precise statistical method of dealing with the predicted annual maxima data.

In 1997, the final Montego Bay study was carried out to map storm surge heights for various return intervals in Montego Bay, regardless of the magnitude of the storm that caused the surge. It should be noted that previous CDMP storm hazard-mapping activities at this location had mapped the effects of individual storms or a group of closely related storms. In this study, the TAOS model was run for all storms in the NHC historical database (approximately 960 storms over the years 1886–1997). Included in the storm surge height estimates were the components of setup due to wave, wind and pressure effects, as well as the astronomical tidal components. For each storm, the estimated surge height was predicted just offshore Doctor's Cave beach.

For the statistical analysis, annual maximum surge values were used to ensure the independence of observations. Multiple statistical distribution curves were fitted to these annual maxima. After careful investigation, the Weibull distribution was selected as the most appropriate distribution, based on goodness of fit to the maximum values and realistic estimates of small probability events (100-year returns and greater).

For the 1997 Montego Bay storm hazard mapping assessment, the 10-, 25-, 50- and 100- year surge heights at Doctor's Cave beach were estimated for the maximum likelihood estimate and the 90 percent, 95 percent and 99 percent confidence levels. A summary of these results is given in the following table.

Table 2. Montego Bay Storm Surge (m) using 2-Parameter Weibull Distribution

Estimate/Confidence Limit	**Return Period (years)**			
	10	**25**	**50**	**100**
MLE	0.97	1.56	2.07	2.61
90% limit	1.15	1.90	2.56	3.28
95% limit	1.20	2.04	2.79	3.62
99% limit	1.34	2.28	3.11	4.06

Jamaica - Kingston Metropolitan Area

The application of the TAOS model for the Kingston Metropolitan Area was similar to the final application for Montego Bay, except that storm surges were computed on a 6 arc-second (≈ 230 m) spatial grid. This spatial grid covered the entire KMA area (a coarser grid was used for the rest of the island) to form a digital elevation model, which allowed for the direct plotting of flood zones. In addition to the surge elevations, model outputs included deep wave heights and peak wind strengths.

Sample results of this modeling for the west-central area of Kingston Harbour are given below in Table 3.

Table 3. Kingston Central Port Storm Surge (m) using 2-Parameter Weibull Distribution

Estimate/Confidence Limit	Return Period (years)			
	10	**25**	**50**	**100**
MLE	2.74	3.85	4.69	5.54
90% limit	3.12	4.52	5.64	6.94
95% limit	3.19	4.80	5.93	7.54
99% limit	3.40	5.51	7.11	8.78

Some of the limitations of TAOS model become apparent in Kingston Harbour. Specifically, the narrow entrance to the harbour, combined with the presence of offshore cays and coral reefs, will likely prevent this level of storm surge from actually occurring. In other areas of the harbour, storm surge levels are reduced, from those shown in the table, by approximately 50%. In addition, the "deep water" wave height computations show unrealistic wave heights within Kingston Harbour.

4.4 Comparison of Storm Surge Estimates – Site Specific Model

In order to develop a better sense of the degree of accuracy of the storm surge predictions made by the TAOS model, a separate set of computations were carried out using a different set of models. In addition, whereas the TAOS model had been used to compute storm surge at Doctors Cave only, four sites were selected for the computation of storm surge in this exercise. The four sites selected were: Montego Bay Airport, Doctors Cave, Montego River and Montego Freeport. This approach was taken so that a better indication of the spatial variation in storm surge along this coastline could be obtained. The methodology for computation of the storm surge elevations is similar to that used for the South Coast Sustainable Development Study (Halcrow, 1998) and is described in the following paragraphs.

Using the NHC Atlantic Tropical Storm Database, all storms passing within 300 nautical miles of Montego Bay were extracted and entered into a spreadsheet. A total of 83 storms were identified. For each storm location within the database, inverse barometric pressure rise was computed according to Equation 1. Mean high water level was assumed, rather than computing the exact tide level at each time step in the computation process.

Maximum wave conditions were obtained using a parametric approach developed by Young (1989) and the spatial variation of wave heights, periods, and directions obtained from a set of nomographs (Young, 1989). Wave set-up was then computed according to the method of Battjes and Stive, (1985). Following this, a statistical analysis was conducted on the resulting inshore surge elevations using the extreme analysis methodology contained in US Army Corps of Engineers program ACES (ver 1.07).

The following tables outline the results of the site-specific storm surge analyses at the four different locations:

Table 4. Doctor's Cave Storm Surge (m) using Weibull Distribution k=1.4

Estimate/Confidence Limit	Return Period (years)			
	10	**25**	**50**	**100**
MLE	1.7	2.1	2.4	2.7
90% limit	1.9	2.4	2.8	3.1
95% limit	2.0	2.5	2.8	3.2
99% limit	2.0	2.6	3.0	3.3

The storm surge values for Doctors Cave compare well at the higher return periods with the values predicted by the advanced TAOS model (Table 2), although the surge heights for the lower return periods are somewhat higher than the TAOS predictions. This may have to do with the fact that every storm passing within 300 nautical miles is included in this analysis, as opposed to the annual maxima analysis, which excludes all but the highest surge in each year.

Table 5. Montego Bay Airport Storm Surge (m) using Weibull Distribution k=1.4

Estimate/Confidence Limit	Return Period (years)			
	10	25	50	100
MLE	1.3	1.6	1.8	2.0
90% limit	1.5	1.8	2.1	2.3
95% limit	1.5	1.9	2.1	2.4
99% limit	1.6	2.0	2.2	2.5

Table 6. Montego Freeport Storm Surge (m) using Weibull Distribution k=1.0

Estimate/Confidence Limit	Return Period (years)			
	10	25	50	100
MLE	1.8	2.5	3.1	3.6
90% limit	2.3	3.1	3.8	4.5
95% limit	2.3	3.2	3.9	4.6
99% limit	2.5	3.5	4.2	5.0

Table 7. Montego River Storm Surge (m) using Weibull Distribution k=1.4

Estimate/Confidence Limit	Return Period (years)			
	10	25	50	100
MLE	1.4	1.7	2.0	2.2
90% limit	1.6	2.0	2.2	2.5
95% limit	1.6	2.0	2.3	2.6
99% limit	1.7	2.1	2.4	2.7

The results show that there is some variability in storm surge predictions along the Montego Bay shoreline, with computed storm surge values varying from a 1.8 m to 2.4 m along the main shoreline (and up to 3.1 at Montego Freeport).

4.5 Mapping of Results

4.5.1 General

In order to present the outputs from the TAOS model (or any storm surge model), base maps are required with appropriate planimetric and topographic details of the study area. TAOS has been established on a GIS, which manages the input spatial relationships of the database and model outputs. The GIS engine is raster based, but is not available for analysis of the output beyond the embedded options.

Even in its detailed format, i.e., the 6 arc-second (200 metre) grid version, the base map used by TAOS in the KMA study does not allow for the specific analysis normally related to physical planning, engineering assessment or emergency management planning and operations.

Mapping required for storm surge assessments at the level of towns and specific communities, present some difficulties. Planimetric maps at scales as large as 1:10,000 will allow for the identification of key infrastructure and social features. Topographic information related to storm surge, is typically required in the elevation range of 0 to 20 metres above sea level. This level of topographic detail is normally associated with mapping at 1:2,500 scale, where contours at 1 metre intervals are presented.

For the Montego Bay project, mapping was required for the entire study area, in order to present the surge data in relation to existing planning set-back regulation, land use zoning, social and infrastructure features and demographic data.

4.5.2 Montego Bay – Existing Maps

The following table lists the significant relevant map series currently available from the Survey Department and other Government of Jamaica agencies, for general public access.

Table 8. List of Existing Map Data

Description of Sheets	Sheets	Date	Scale	Contour
Topographical Map Series:				
Topographical Map of Jamaica	1		1:250,000	1000 ft.
Map of Jamaica	12		1:100,000	
Topographical Map of Jamaica DOS 410			1:50,000	250 ft.
Topographical Map of Jamaica (Metric) JSD/DOS 1982	20	1982	1:50,000	40 m
Montego Bay Topo-Series DOS 301/1	1		1:25,000	50 ft.
All Island Mapping, Jam. 201	232		1:12,500	25, 50 ft.
Planimetric Map Series:				
Montego Bay	38	1954	1:1,250	
Montego Bay – Metric unpublished	12	1989	1:2,500	2 m
Land Valuation Department,				
Grid Maps (Montego Bay)			1:10,000	
Aerial Photographs:				
All Island Aerial Colour Photography, Trees for Tomorrow		1991	1:15,000	
Major Urban Areas, Kingston, MoBay, Trees		1992	1:5,000	

4.5.3 Montego Bay – Mapping Exercise

In order to obtain the digital mapping required for the GIS analysis, it was decided to prepare a base map from the 1:15,000 - 1991 colour photographs of the study area. This data source represented the most current information. Further, it was determined that this base map would be in the form of an ortho-rectified image which would make all of the visual features available for the creation of coverages and data for analysis. Topographic details from the unpublished 1:2,500 maps would be used for the creation of vector based contours, from which a TIN or DEM could be created and specific contours generated as required to match the TAOS output.

Production of the ortho-rectified image was achieved by following a novel process, whereby the available data was used to produce a very detailed base map image at relatively low cost. ERDAS IMAGINE 8.3 software was the principal tool used for the mapping process. Ortho-rectification of images involved the following process:

- Aerial photograph contact prints at 1:15,000 scale, were scanned at 600 dpi resolution to create digital aerial imagery. Un-published Survey Department 1:2,500 maps were then scanned and geo-referenced.
- Plan control for scaling and orientation within the national grid was extracted from the 1:2,500 maps and vector elevation coverage. The digital aerial imagery was geo-referenced.
- Land elevation contours were digitized (heads up) from the raster maps, along with the elevation points shown on the ground, to create a digital vector coverage of the study area. This would facilitate the creation of a DEM for terrain relief correction.
- The digital aerial image was then ortho-rectified using pixel-by-pixel single frame techniques available in ERDAS IMAGINE 8.3 software. The individual frames were then re-sampled and a mosaic image created. The image base map and vector contour coverage was suitable for importing into ESRI ARCVIEW 3.1 software for GIS analysis.

The cost of preparing the base map and vector elevation coverage was less than US$1 per hectare compared to approximately US$10 or greater per hectare, for traditional approaches to preparing ortho-rectified aerial images.

4.5.4 Montego Bay – Description of the GIS Model (Metadata)

A GIS model was created in ARCVIEW for the analysis of the spatial data compiled for the Montego Bay study area. The significant spatial features of the study area, in relation to coastal zone planning, were obtained from the following sources:

Land Use Zoning 1983
Town and Country Planning Authority; St. James Parish Council
Source: 1:25,000 map from St. James development Order

HWL Step Back requirement for buildings
Town and Country Planning Authority; St. James Parish Council
Source: Development Manual (Green Book)

CENSUS 1991 – Demography
Database for population, private dwellings by enumeration districts
Statistical Institute of Jamaica
Source: Published digital maps

Base Map, 1:15,000 colour aerial photography, Tree for Tomorrow Series 1991
Ortho-rectified with controls and topography taken from SD 1:2500 maps series
Processing software, ERDAS Imagine 8.3

Base Map, 1:2,500 Survey Department (unpublished) scanned and geo-referenced.
Topography spot elevations data reproduced as ARCVIEW shape files.

By overlaying the above data on the base maps produced, along with the elevation lines for the storm surges predicted by the TAOS model for the 1 in 25 and 1 in 50 year return period storms, the implications of the storm surge with respect to these parameters, were analyzed.

4.6 Discussion of Results of Spatial Analysis

4.6.1 Surge Impacts on Land Use

The coastal zone of the study area is planned for resort, resort/residential, transportation, conservation, commercial and office, institutional, light industry, open space, public assembly, public buildings, agriculture and residential use.

The storm surge generated for the 1 in 25 and 1 in 50 year storm surges (Figures 4.1 and 4.2) will impact significantly on some of these development zones. The following table sets out the land area occupied by each zone and the area that will be inundated by the 1 in 25 and 1 in 50 year storm surges. The regulated land area covered by the 100 foot Town Planning Department set-back provision is also tabled.

Table 9. Land Use Areas Affected by Storm Surge

	Areas in hectares			
LAND USE	**100 ft Step Back**	**25 yr Surge**	**50 yr Surge**	**Land Use Zones**
Agriculture	0.00	9.36	22.04	192.07
Cemetery	0.00	0.00	0.00	2.19
Commercial + Office	8.78	14.96	36.48	106.47
Conservation	18.57	100.80	105.73	120.14
Institutional	0.00	4.15	7.00	61.49
Light Industry	8.07	41.47	111.78	167.22
NWC - Sewage	0.41	0.15	6.17	6.18
Open Space	8.36	9.26	17.74	30.70
Public Assembly	5.52	13.17	13.35	14.37
Public Building	0.00	2.43	3.59	5.31
Residential	0.00	0.00	1.41	32.69
Resort	35.65	95.61	116.80	160.00
Resort / Residential	0.00	0.00	0.58	221.96
Transport	2.59	181.69	225.70	254.50
UDC	1.39	10.87	22.73	25.67
TOTAL	**89.34**	**483.92**	**691.10**	**1400.96**

A quick analysis of the above table shows that the conservation, commercial and office, resort, transport (airport) and light industry areas are those primarily affected by the 25 year storm surge line in comparison to the 100 foot set back provision.

For the 1 in 50 year storm surge, significant additional areas of commercial and office, light industry and transport become affected. It is noteworthy that the coastal zone of the Montego Bay area has very little residential land use. The site of the Catherine Hall residential area, developed by the UDC, was filled to approximately 2.5 metres above MSL and is well protected.

The economic implication of a 25 or 50-year storm surge event for the city is quite significant however. The city’s main income is from tourism and employment is mainly in the tourism sector and light industry. Both of these sectors will be subject to significant impact from such events.

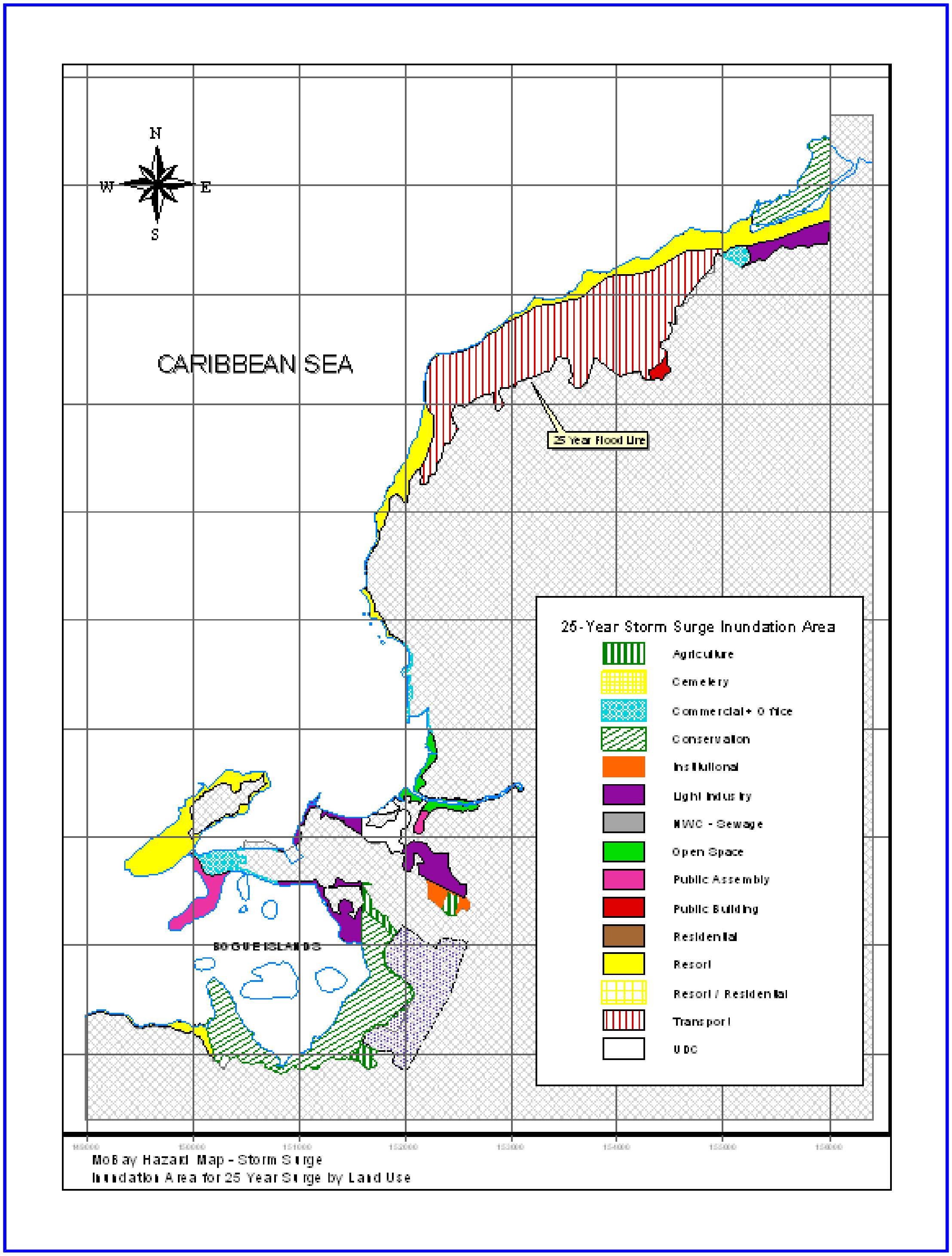

Figure 4.1 Inundation Area for the 1 in 25 Year Hurricane Surge

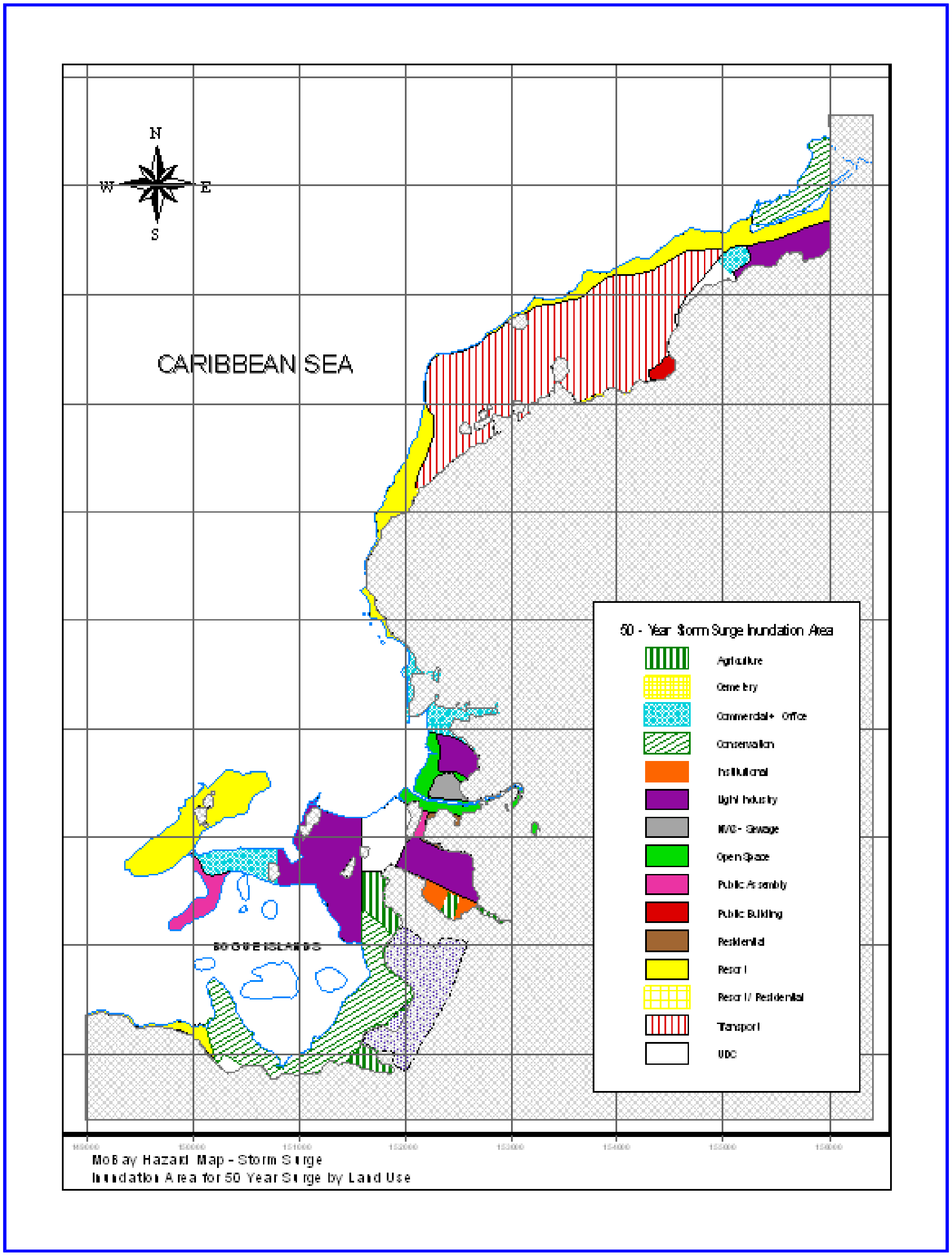

Figure 4.2 Inundation Area for the 1 in 50 Year Hurricane Surge

4.6.3 Surge Impact on Critical Infrastructure

Following is a summary of impacts identified for critical infrastructure in the coastal zone of Montego Bay.

- The new Divisional Police Station shown on Figure 4.3 is expected to stay dry up to a 1 in 50 year storm surge.
- The new main NWC sewage pump station will most probably be inundated. Special emergency management provisions will be necessary to ensure that as soon as elevated water levels subside, the station can be returned to service.
- The Sangster International Airport will be inundated for storm surge events of 1 in 25 years or greater. Again, special emergency management provisions will be necessary to ensure that as soon as elevated water levels subside, the facility can be returned to service.

The impact of elevated water levels on electricity supplies, water supply, sewage facilities, drains and roads, all need to be more specifically analyzed. The base map and DEM data available with the hazard map GIS model, will greatly facilitate such detailed specific analysis.

The banks of the North Gully, South Gully and the Montego River pose significant risks, as elevated water levels at sea will affect the flood regime in these watercourses. Swift moving floodwaters, which encounter unprotected embankments and structures, are likely to cause significant erosion and damage to adjacent areas.

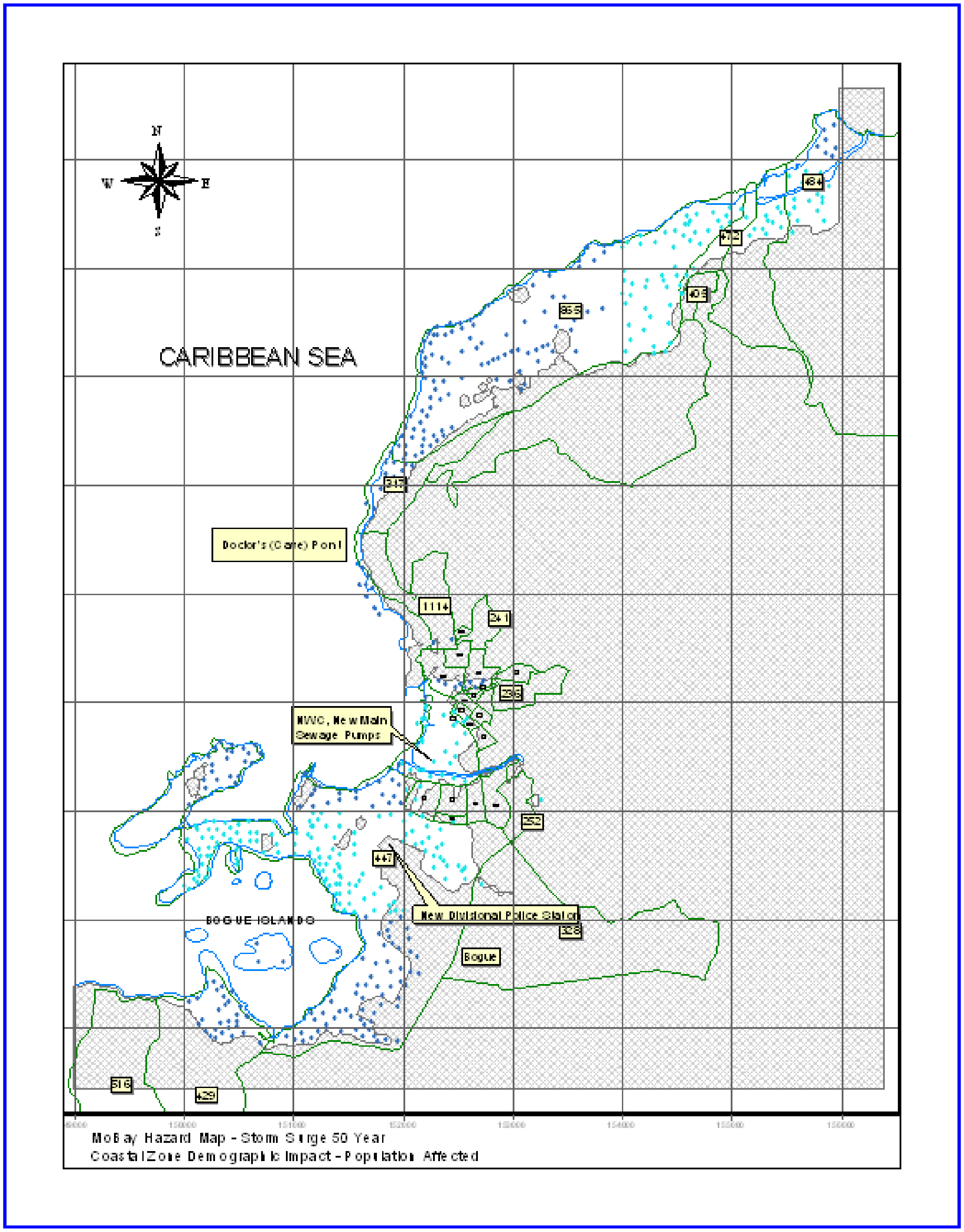

Figure 4.3 Impacts of Storm Surge on Population/Housing

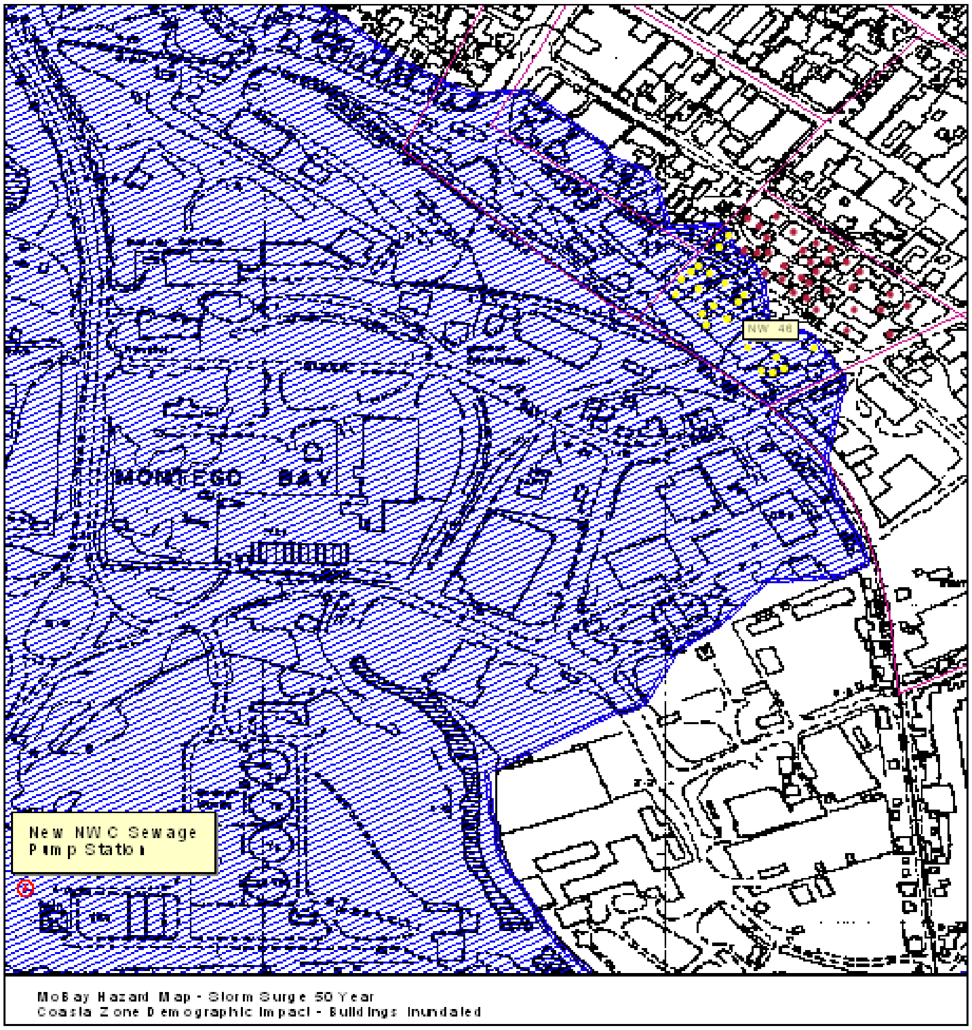

Figure 4.4 Details of Inundation Area Under the 50-Year Storm Surge

Figure 4.5 Detailed Ortho-Photo of 50-year Flooded Area

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